

A comprehensive review of rock dust for soil remineralization in sustainable agriculture and preliminary assessment of nutrient values in micronized porous basalt rock from Nghe An province, Viet Nam

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Abstract. This review examines the use of rock powder as a mineral-derived fertilizer to promote soil remineralization in sustainable agriculture. Soil remineralization has emerged as a key strategy for ensuring long-term soil fertility and reducing reliance on synthetic fertilizers. This review critically assesses the methodological approaches employed in various studies, considering factors such as local rock mineralogy, soil conditions, crop types, and plant nutrient uptake. The review encompasses methods such as nutrient value analysis, nutrient release rate assessment, and crop cultivation experiments conducted in both laboratory and field settings, as well as implications for soil remineralization. Additionally, we present findings from a preliminary study on the nutrient content of basalt rock from Nghe An Province, Vietnam. This investigation focuses on assessing the nutrient values in a specific porous basalt material processed into micro- and nanometer-sized particles using a high-energy ball mill, thereby enhancing the efficiency of nutrient release. The study employs various analytical techniques, including XRD, XRF, SEM/EDS, and ICP-MS, to quantify macro- and micro-nutrient compositions. While basalt rock samples may exhibit limitations in providing macronutrients (like K) compared to commercial azomite rock, they offer advantages in supplying secondary macronutrients (such as Ca). This analysis provides insights into the potential use of micronized basalt rock for soil remineralization.

Keywords: soil remineralization, stonemeal, mineral-derived fertilizer, basalt rock, sustainable agriculture.

Classification numbers: 2.9.2, 2.10.2, 2.10.3.

1. INTRODUCTION

According to Tilman et al.'s research [1], global cereal production has doubled over the past 40 years, mainly due to increased fertilizer use, technological advancements, and the development of crop strains. Between 1960 and 1995, nitrogen fertilizer use grew sevenfold, and

phosphorus use increased 3.5 times. Both are projected to triple by 2050 unless fertilizer efficiency improves. Synthetic fertilizers have been crucial for expanding food production and preventing the conversion of natural ecosystems into farmland. They are now crucial for enhancing biomass production in agriculture. By 2050, with the global population projected to increase by 50% and grain demand doubling, improving agricultural output will remain vital for global stability, equity, and food security.

1.1. Nutrient demand and the challenge of soil depletion in agriculture

Table 1. Sixteen plant essential nutrients and their forms, sources, and modes of uptake [3].

Nutrient family	Nutrient	Percentage of plant	Form taken up by plants (ion)	Mode of uptake	Major function in plants
Primary	Carbon	45	Carbon dioxide (CO_2), bicarbonate (HCO_3^-)	Open somates	Plant structures
	Oxygen	45	Water (H_2O)	Mass flow	Respiration, energy production, plant structure
	Hydrogen	6.0	Water (H_2O)	Mass flow	pH regulation, water retention, synthesis of carbohydrates
	Nitrogen	1.75	Nitrate (NO_3^-), ammonium (NH_4^+)	Mass flow	Protein/amino acids, chlorophyll, cell formation
	Phosphorus	0.25	Dihydrogen phosphate (H_2PO_4^-), HPO_4^{2-} , phosphate (PO_4^{3-})	Root interception	Cell formation, protein syntheses, fat and carbohydrate metabolism
	Potassium	1.5	Potassium ion (K^+)	Mass flow	Water regulation, enzyme activity
Secondary	Calcium	0.50	Calcium ion (Ca^{2+})	Mass flow	Root permeability, enzyme activity
	Magnesium	0.20	Magnesium ion (Mg^{2+})	Mass flow	Chlorophyll, fat formation and metabolism
	Sulfur	0.03	Sulfate (SO_4^{2-})	Mass flow	Protein, amino acid, vitamin and oil formation
Micro	Chlorine	0.01	Chloride (Cl^-)	Root interception	Chlorophyll formation, enzyme activity, cellular development
	Iron	0.01	Iron ion (Fe^{3+} , Fe^{2+})	Root interception	Enzyme development and activity
	Zinc	0.002	Zinc ion (Zn^{2+})	Root interception	Enzyme activity
	Maganese	0.005	Manganese ion (Mn^{2+})	Root interception	Enzyme activity and pigmentation
	Boron	0.0001	Boric acid (H_3BO_3), borate (BO_3^{3-}), tetraborate (B_4O_7)	Root interception	Enzyme activity
	Copper	0.0001	Copper ion (Cu^+)	Mass flow	Enzyme activity
	Molybdenum	0.00001	Molybdenum ions (HMoO_4^- , MoO_4^{2-})	Mass flow	Enzyme activity and nitrogen fixation in legumes

Different crops have distinct nutrient demands that can vary significantly. To achieve optimal growth and productivity, it is essential to manage the specific fertilizer for each crop, following the principle of the Four Rs: correct rate, proper nutrients, right time, and right place (terminologies promoted by the International Plant Nutrition Institute) [2]. Nutrients can be categorized into macronutrients, secondary macronutrients, and micronutrients based on the quantities required by plants. Macronutrients, such as nitrogen (N), phosphorus (P), and potassium (K), are critical for crop growth. Additionally, crops require secondary macronutrients like calcium (Ca), magnesium (Mg), and sulfur (S), as well as micronutrients including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo). Plants need macronutrients in larger quantities compared to micronutrients, which are necessary in trace amounts. Both types of nutrients are crucial for vital physiological processes [3].

In practice, crops absorb nutrients in various chemical forms: nitrogen as nitrate (NO_3^-) and ammonium (NH_4^+), phosphorus as phosphate (H_2PO_4^- and HPO_4^{2-}), and potassium as K^+ . Other nutrients are taken up as oxides, sulfates, or chelates. These chemical forms determine nutrient availability and uptake efficiency. Table 1 summarizes nutrients and their forms [4].

Nutrient deficiencies severely affect crop growth and productivity, causing stunted growth, reduced yields, poor quality, and greater susceptibility to pests and diseases [4]. Nitrogen

deficiency leads to chlorosis and reduced photosynthesis, while phosphorus deficiency causes poor root development and delayed flowering. Identifying and correcting deficiencies is essential for rice crop health and maximum productivity.

Synthetic fertilizers have provided an effective means to increase crop yields, but excessive use, erosion, and unsustainable practices have degraded soils and disrupted nutrient balance, leading to pollution. Sustainable agriculture requires correcting soil nutrient deficiencies while mitigating the adverse effects of synthetic fertilizers [1].

1.2. Soil remineralization and its mechanism of providing nutrients in sustainable agriculture

Conventional farming practices often rely on continuous cultivation without adequate replenishment of essential nutrients. These methods depend on synthetic fertilizers that primarily supply macronutrients such as nitrogen, phosphorus, and potassium, neglecting essential minerals and trace elements (micronutrients). Consequently, this approach leads to the depletion of natural nutrient reservoirs in agricultural soils, resulting in diminished crop yields and unsustainable practices. The concept of mass food production through intensive soil manipulation, industrial inputs, irrigation, and mechanization, known as the Green Revolution, emerged as a response to the global food production crisis, population growth, and concerns about food availability [5]. However, widespread chemical fertilizer use has disrupted the balance of the agricultural sector, creating dependencies on imported materials and exacerbating the challenges posed by low-fertility soils, which are often acidic and nutrient-deficient, particularly in terms of phosphorus and potassium [6].

Recognizing the need to address nutrient depletion, soil remineralization, or stonemeal, has emerged as a promising strategy in sustainable agriculture. This practice incorporates rocks and minerals into soil, with liming as a notable example [7]. It reduces reliance on synthetic fertilizers, restores degraded soils, maintains balanced fertility, conserves resources, and sustains productivity [8]. While Justus von Liebig's discovery of NPK in the 1890s initiated the chemical fertilizer era, Julius Hensel argued in *Bread from Stone* (1894) that powdered rocks could achieve similar effects at lower cost and without environmental harm [9]. Though initially overlooked, his work regained attention with the 1997 reissue, reflecting growing concerns about nutrition and food safety. Today, rock powders are valued as alternative nutrient sources to highly soluble NPK formulations [10]. Studies suggest they can reduce fertilizer expenses by up to 50% [11]. In addition to cost savings, rock powders transform waste into useful products and expand market opportunities for mineral-based fertilizers.

Rock powder, or rock dust, is an inexpensive, locally produced material widely recommended for soil remineralization [12]. It helps balance soil nutrients by supplying essential minerals and trace elements. Common sources include basalt, granite, limestone, and volcanic rock dust. Basalt, an igneous rock, is rich in calcium, magnesium, iron, and trace elements such as manganese and zinc, making it a key material for soil remineralization. Granite provides potassium, phosphorus, and silica. Limestone, mainly calcium carbonate, raises soil pH and supplies calcium, while volcanic rock dust delivers minerals and trace elements accumulated over millions of years. Each type of rock mineral offers unique advantages to the soil and plants. Volcanic rock, for instance, consists mainly of SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , MgO , Na_2O , K_2O , and CaO [13].

Soil remineralization involves the breakdown of rock minerals, releasing essential nutrients into the soil over time. This occurs through mechanisms like mineral weathering, cation exchange, and microbial activity. Mineral weathering is a natural process where rock minerals react with water, oxygen, and organic acids, gradually releasing elements in forms plants can absorb. As these minerals weather, positively charged ions (cations) such as Ca^{2+} , K^{+} , and Mg^{2+} are released and can exchange with other cations on soil particles. Microbial activity also plays a crucial role in soil remineralization. Beneficial microorganisms, including bacteria and fungi,

interact with rock minerals, facilitating their breakdown and subsequent release of nutrients. These microorganisms produce organic acids and enzymes that facilitate weathering, enhancing nutrient availability. This process ensures improved nutrient access, enabling plant roots to acquire necessary nutrients effectively.

The effects of soil remineralization can persist for years due to the gradual release of nutrients. Rock powder enhances soil cation exchange capacity through the formation of new clay minerals during mineral alteration [14]. Nutrient release from rock lattices occurs via organic acids produced by plants and soil microorganisms [15]. The effectiveness of remineralization depends on the mineral characteristics of the rock and its interaction with the environment, which together improve soil fertility [11].

One example illustrating the positive effects of applying high concentrations of basaltic rock to low-fertility soil was described by Melamed *et al.* [16]. Such a study demonstrated a significant increase in pH and cation exchange capacity after twelve months of incubation, with more pronounced effects observed with smaller particle sizes and longer contact times between the material and soil. Gillman *et al.* [17] investigated the behavior of soils from seven Queensland sites incubated with different concentrations of basalt particles (0.1, 5.25, and 50 t/ha). They observed significant increases in pH, cation exchange capacity, and levels of alkali cations.

In 1998, Escosteguy and Klant reported that ground rocks release nutrients slowly and cannot serve as a primary nutrient source, though small doses increased potassium, calcium, magnesium, and soil pH. Unlike chemical fertilizers, which provide immediate but short-lived effects, rock dust acts in the medium to long term, offering more durable improvements in soil fertility [18].

Blum *et al.* [19] noted that rock particles release nutrients very slowly. Their low solubility raises doubts about effectiveness as a soil nutrient source, often requiring large quantities for measurable effects [20]. Dissolution is a slow, complex process influenced by mineral composition, particle size, soil pH, biological activity, and weathering.

1.3. Benefits, challenges in previous research and application of rock dust for soil remineralization

Soil remineralization is an alternative method for fertilization that improves the physicochemical characteristics of the soil. It mitigates the negative environmental impacts associated with high-cost synthetic fertilizers, which can harm small-scale agriculture. Crops can reach their maximum productivity by providing essential nutrients, resulting in higher yields of quality fruits, vegetables, grains, and other products. Furthermore, remineralized soil enhances the flavor and nutritional value of agricultural products. The balanced supply of minerals and trace elements enriches the taste, aroma, and sensory qualities of fruits, vegetables, and herbs. Research suggests that remineralization can enhance the nutritional content of crops, promoting the abundance of vitamins, minerals, and beneficial phytochemicals for human health and well-being [21]. Incorporating rock powder into the soil enhances water-holding capacity, reducing runoff and improving retention, which is particularly useful in arid or drought-prone regions. Moreover, soil remineralization promotes overall soil health by supporting beneficial microorganisms in nutrient cycling and the decomposition of organic matter, thereby contributing to long-term fertility and increased crop yields.

Experiments and research on the utilization of powdered rocks have been conducted globally, including notable contributions by James Hutton in the eighteenth century [22]. Hutton, widely recognized as the pioneer of geological sciences, applied loam and similar rocks to enhance soil fertility on his Scottish farm. The potential of rock-derived nutrients was further emphasized by Lacroix [23], who highlighted the significance of incorporating various rocks for agricultural purposes. Graham suggested using plagioclase as a calcium source based on experimental data [24]. At the same time, Keller advocated for utilizing various rock types as

sources of potassium, calcium, and trace elements, promoting the practice of stonemeal [25]. D'hotman de Vulliers recommended the application of powdered basalt rock in Congo for rejuvenating depleted soils, demonstrating significant increases in cane sugar production through field experiments [26]. Evans observed substantial improvements in dry matter production with oats cultivated in pots using basaltic rock powder at varying rates. Il'chenko and Guimarães highlighted the potential of Cedro do Abaeté, Serra da Mata da Corda, and Poços de Caldas rocks in Brazil [27]. Fraya conducted surveys on phonolites, which showed high levels of K_2O alteration, indicating their potential as rock powder fertilizers [28]. Kavaleridze reported that predominant basaltic rocks in southern Brazil are rich in silica, calcium, magnesium, and potassium, recommending their conversion into powder for stonemeal application [29]. Motta and Feiden found that applying 40 t/ha of basalt powder effectively raised the available phosphorus level, serving as corrective fertilization for the soil [30]. Kiehl noted positive results with basalt rock dust as a soil amendment, making it a favorable alternative for farmers, recommending the application of 50-100 t of basalt powder per hectare in poor soils to enhance fertility [31].

The Remineralize the Earth (RTE) program is a leading initiative in large-scale soil remineralization using rock dust. Through global projects applying basalt and granite, RTE has achieved notable gains in soil fertility, crop yields, and nutrient enrichment of harvested produce [32]. The achievements of the RTE program serve as a testament to the effectiveness of soil remineralization through the use of rock dust. RTE has advanced remineralization techniques and raised awareness about the crucial role of soil health and the importance of rock dust in sustainable agriculture. Indigenous farming communities worldwide have long incorporated rock minerals, such as volcanic dust, into agriculture. These practices support sustainable food production, improve soil fertility, and strengthen resilience in difficult conditions. By using rock dust's mineral properties, indigenous farmers have replenished soil nutrients and improved its quality. This has enabled them to cultivate crops resilient to drought, pests, and diseases, showcasing their resourcefulness and ingenuity [33]. Furthermore, organic farms in the U.S. and Europe have integrated soil remineralization into their operations. These farms report improved soil health, nutrient availability, and yields from rock minerals, which also balance nutrients, enhance soil structure, and support beneficial microorganisms. Consequently, organic farms that implement soil remineralization experience improved soil fertility, resulting in increased crop productivity and sustainability [34].

While soil remineralization using rock minerals offers numerous benefits, it is essential to acknowledge the associated challenges and limitations. One major challenge is the cost of obtaining and applying rock mineral amendments. High-quality rock minerals are costly for large-scale use, with transportation and application adding further expense. Another challenge is the need for long-term application and monitoring. Soil remineralization is an ongoing process requiring regular application and monitoring to sustain optimal nutrient levels. The rate of mineral breakdown and nutrient release varies with factors like soil type, climate, and microbial activity. Regular soil testing and analysis are crucial to ensure balanced mineral ratios and sufficient nutrients for plant growth and productivity. Achieving a proper balance of mineral ratios is essential for optimal growth. Although rock minerals provide many essential nutrients, their ratios matter, as imbalances can harm plant health, causing deficiencies or toxicities [34].

1.4. Micronized volcanic rock as a potential mineral derived fertilizer

In recent years, micronized volcanic rock has become a valuable mineral-derived fertilizer for soil remineralization [21]. Micronization technology involves finely grinding natural rock into particles of micron-sized dimensions, typically ranging from a few micrometers to tens of micrometers (Figure 1). Specialized equipment, such as ball mills or jet mills, is utilized in this process to achieve the desired particle size. Compared to natural rock dust, micronization significantly increases the surface area of the volcanic rock, facilitating greater contact between the soil and mineral particles. This expanded surface area plays a crucial role in enhancing the effectiveness of volcanic rock as a fertilizer by increasing nutrient release and improving its

availability to plants. The micronized particles establish a closer contact with the soil, enabling the minerals to weather and release essential nutrients over an extended period gradually. This slow-release characteristic ensures a sustained nutrient supply to plants, reducing the risk of nutrient leaching and optimizing nutrient uptake efficiency. Additionally, micronization facilitates the breakdown of complex mineral structures within volcanic rock, making the nutrients more readily accessible to plant roots [35]. Consequently, the use of micronized volcanic rock as a fertilizer promotes robust plant growth, increased crop yields, and soil fertility.



Figure 1. Commercial azomite rock of Azomite Mineral Products, Inc-USA (adapted from website [35]).

Micronized volcanic rock has a positive impact on soil health and crop yields, leading to increased research efforts in this area. Various approaches can be employed to apply micronized rock to the soil, depending on the needs and characteristics of the agricultural system [36]. One method involves applying micronized rock to the soil surface, which can be incorporated into the topsoil through mechanical means, such as tilling or harrowing. This ensures contact between the minerals and soil, facilitating the breakdown and release of nutrients. Another approach mixes rock minerals with compost or organic matter before application. This promotes nutrient integration and enhances the organic matter content of the soil, improving its structure, moisture retention, and nutrient-holding capacity. In some cases, micronized rocks can also be applied as foliar sprays directly onto plant leaves. This allows for direct absorption of minerals by the foliage, supporting plant health. Determining optimal application rates and timing of rock minerals depends on soil composition, crop type, nutrient requirements, and local climatic conditions. Conducting soil tests to assess deficiencies and determine appropriate application rates is crucial.

Investigating powdered rock as a potential fertilizer, considering nutrient content, release, economic viability, and market potential, remains a global research necessity. Therefore, this study aims to characterize the micronized porous basalt rock sourced from Nghe An Province, Vietnam, in relation to commercial azomite rock. We conducted various material analyses and tests to evaluate the nutrient release properties of this basalt rock and its potential to supply macro- and micro-nutrients, thereby enhancing soil fertility. Furthermore, this research aims to pave the way for future studies on utilizing such micronized basalt rock as a substitute for chemical fertilizers.

2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Volcanic rocks and chemicals

The porous basalt rock (Figure 2a) is currently used in the building materials industry, serving as a mineral additive and lightweight aggregate. It is characterized by a gray-brown color, an interconnected porous structure, and a diameter of approximately 10-50 cm. This type of basalt is formed through the rapid cooling of volcanic basalt lava, accompanied by the infiltration of air. It possesses a high water absorption capacity and tends to break easily upon slight impact. In Nghe An province, the distribution of pumice basalt is concentrated in Nghia Dan district, with estimated reserves ranging from 70 to 100 million tons.

To prepare the micronized basalt material, basalt rock undergoes preliminary crushing to reduce its size to 0.1 - 1 cm after washing with tap water. The material is then ground in a high-energy ball mill machine at Saigon Nanomaterials Co., Ltd. The grinding process takes about 45 minutes and uses stainless steel balls for ultra-fine grinding. This industrial-scale ball mill consists of four steel containers. The resulting mixture forms a colloidal suspension with a small amount of organic dispersant (polycarboxylate ether, PCE), allowing the suspension to flow easily and be extracted using a diaphragm pump. Commercial azomite micronized ($D_{90} < 74 \mu\text{m}$), sourced from Azomite Mineral Products, Inc - USA, was used without further purification. The experiment involved grinding the micronized azomite in a high-energy ball mill, a process similar to that used for basalt rock. The porous basalt rock exhibits characteristics like commercial azomite rock, being soft and easily grindable. Distilled water ($\text{pH} = 7.8$) was used in the dissolution of micronized rock. Citric acid ($\text{C}_6\text{H}_8\text{O}_7$, 99.9%) from Xilong was used at analytical grade without purification in the leaching test.

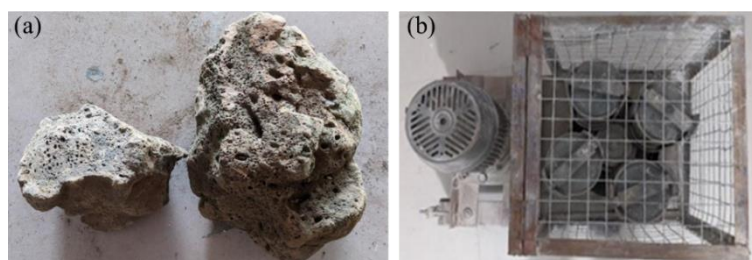


Figure 2. (a) Porous basalt rock from Nghe An province; (b) High-energy ball mill developed by Sai Gon Nanomat Co., Ltd.

2.2. Experimental methods

Various analytical techniques were employed to characterize ground basalt rock materials. The stability of different batches of colloidal samples was checked using Brunauer–Emmett–Teller (BET) surface area analysis on a Quantachrome NOVA 2200E. Particle size and elemental composition were determined through Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM/EDS) using a Hitachi S-4800 FE-SEM. X-ray diffraction (XRD, EMPYREAN - PANalytical) was used to identify mineral composition, and an X-ray fluorescence spectrometer (XRF, ARLADVANT'X-ThermoScientific) determined the percentage of oxides in fine powder samples. ICP-MS (Inductively Coupled Plasma–Mass Spectrometry) quantified the elemental composition in raw materials and extracted solution samples. These analytical methods provided insights into the properties, composition, and stability of the basalt rock materials.

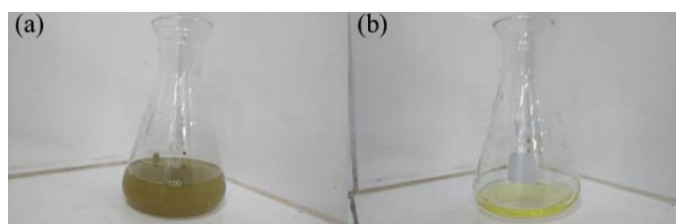


Figure 3. (a) Solubility of micronized basalt rock in acidic solution after 30 minutes of shaking time, (b) Solution under vacuum filter for ICP-MS analysis.

The water dissolution method of micronized rock followed the guidelines in EN 12457-2:2002. The leaching test using acidic solutions replicates the soil environment during nutrient uptake by plant roots, as noted in a study by Ramos et al. [15]. Various factors, including temperature, type of extraction solution, solid-to-solution ratio, number of extractions, stirring

speed, particle size, and pH, influence the release of nutrients in the extraction solution. Notably, pH plays a significant role, often characterizing the acidic environment near the roots of secretory plants, which facilitates the dissolution of nutrients. In the nutrient leaching experiment, a 2% wt citric acid solution served as the extraction medium, with continuous pH monitoring (pH = 2.2). The solid/distilled water dissolution ratio was maintained at 1 g/100 mL, and Erlenmeyer flasks were shaken for 30 minutes (with acid) or 1440 minutes (with distilled water) to promote dissolution (Figure 3-a). The extracted solution samples underwent vacuum filtration (Figure 3 b) and were stored for 4 hours before undergoing quantitative analysis of K, Ca, and Al using the ICP-MS method.

3. RESULTS AND DISCUSSIONS

3.1. Results of analysis of micronized basalt rock

The specific surface area measurement of the ground basalt suspension sample yielded 41.11 m²/g, with a high level of confidence. This indicates a significantly larger specific surface area than the ground limestone sample in our previous publication (16 m²/g) [37]. The equivalent average particle size is estimated to be in the micro- to nanometer range, which aligns with expectations given the softer, more crushable nature of porous basalt rock.

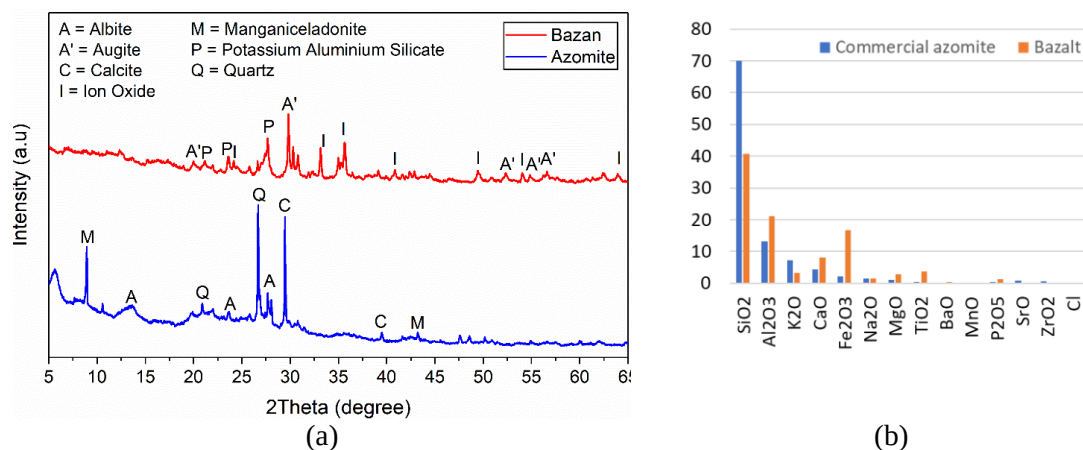


Figure 4. XRD spectrum of basalt rock from Nghe An province and commercial azomite rock (a) and Results of oxide composition analysis (wt.%) by XRF method (b).

Figure 4 reveals the primary mineral components of the basalt rock sample: augite, potassium aluminum silicate (mica), and iron oxides. Mica, from the alkaline feldspar group, has low resistance to weathering, making it prone to dissolving nutrients. Augite, a mineral from the pyroxene group, has limited stability and can release Mg, Fe, and Ca, facilitating new mineral formation. In contrast, the Azomite rock sample consists of quartz, albite, manganiceladonite, calcite, and manganiceladonite. Albite, like mica, belongs to the feldspar group. Quartz and calcite are known for their contributions of calcium and silicon.

Referring to Figure 4-b, the main oxide compositions of the two volcanic rocks include SiO₂, Al₂O₃, K₂O, CaO, Fe₂O₃, Na₂O, and MgO. Basalt has a lower SiO₂ content (40.70 %) compared to Azomite (70.00 %). This difference is due to the mineral composition of azomite, which contains quartz (SiO₂) and albite (NaAlSi₃O₈), while basalt contains mica (an alkaline feldspar). Basalt shows higher CaO (8.04 % vs. 4.29 %) and Fe₂O₃ (16.07 % vs. 2.10 %), as well as MgO (2.80 % vs. 1.01 %), compared to azomite. Notably, potassium oxide content in azomite is significantly higher than in basalt (7.12 % vs. 3.25 %).

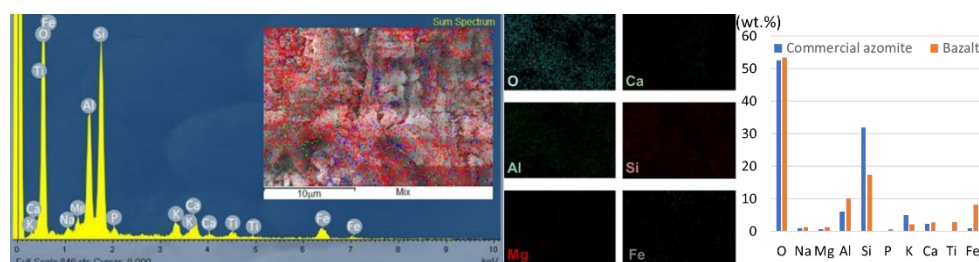


Figure 5. SEM/EDS spectrum of basalt rock from Nghe An province, chemical elements distribution, Elemental composition (wt.%) estimated by SEM/EDS analysis.

Table 2. Results of elemental composition analysis by the ICP-MS method.

Elemental composition (by ppm)											
	Ag	Al	As	B	Ba	Be	Bi	Cd	Co	Cr	
Commercial azomite	0.43	15863.78	2.00	225.61	259.72	0.49	21.76	-	1.51	186.29	
Bazalt	1.20	27377.89	1.73	216.24	333.18	0.70	0.76	-	12.77	184.74	
	Cs	Cu	Ga	Ge	In	K	Li	Mg	Mn	Mo	Na
	1.88	3.93	35.95	0.16	0.01	9981.48	10.16	2798.01	321.58	6.23	2633.43
	0.16	13.20	55.64	0.41	0.03	2806.49	2.72	16149.49	590.09	1.34	1542.46
	Pb										
	8.19										
	Rb	Se	Si	Sr	Ti	Tl	U	V	Zn	Ca (%wt)	Fe (%wt)
	42.02	-	557.52	53.67	333.53	0.17	0.75	7.68	25.65	0.57	8.60
	8.58	-	543.44	161.39	4482.65	0.05	0.41	55.91	39.67	1.64	1.98

Table 2 reveals key distinctions between azomite and basalt rock. Azomite has three times more potassium (K) content than basalt. Basalt contains higher secondary elements, calcium (Ca) and magnesium (Mg), than azomite. While the ICP-MS analysis indicates higher iron (Fe) content in azomite, the XRF and XRD results imply a significant presence of iron oxide traces in basalt rock. We will revisit this point later in the discussion. Basalt rock also has more copper (Cu) and manganese (Mn) than azomite. Both samples contain potentially harmful aluminum (Al), with basalt containing a significantly higher amount. This high Al content in basalt rock can limit its use in plant applications.

The SEM image reveals a distribution map of elements on the cutting surface of the basalt rock sample (Figure 5). Mass percentages of elements in the basalt rock sample are presented in Table 4, estimated through SEM/EDS spectra. Among these, O has the highest mass percentage (53.24 %), followed by Si (17.29 %), Al (10.14 %), Fe (8.18 %), Ti (2.87 %), Ca (2.71 %), K (2.15 %), Na (1.26 %), Mg (1.25 %), and P (0.73 %). Compared to the azomite rock sample, the basalt shows higher levels of Al, Mg, Ca, and Fe, alongside lower levels of K and Si, which aligns with the XRF analysis results. While there are discrepancies in elemental contents by ICP-MS, including Na, Si, Ca, and Fe, careful analysis of XRD and XRF spectra reveals a higher iron oxide content in basalt than azomite. Furthermore, the producer of azomite indicates low iron oxide and iron content by ICP-OES [38]. Variations in values stem from the fact that SEM/EDS estimated values were derived from the surface image detection spectrum. Based on the comparison of main elements like K, Si, Ca, Mg, and Fe, the porous basalt sample shows higher concentrations of secondary and micronutrient elements, whereas azomite has a greater macronutrient composition. However, it is crucial to consider the solubility of these elements, as it directly influences their capacity to supply nutrients to plants.

3.2. Results of nutrient leaching in the extracted solution

The dissolution test results in distilled water (pH = 7.8) reveal that commercial azomite rock exhibits higher solubility than basalt rock for elements K and Ca. Conversely, basalt rock demonstrates higher solubility for element Al. However, considering the total element content in the sample, the concentrations of dissolved K, Ca, and Al in the distilled water solution over 24 hours are very low for both rocks samples. Thus, despite the fine grinding, the release of

nutrients can be considered slow. In the acid solution dissolution test (pH = 2.2), a lower pH of the extraction solution leads to higher nutrient content dissolved in the extract within the same timeframe. The acidic solutions enhance the conversion capacity of nutritional elements in volcanic rock as it becomes more susceptible to weathering. This finding aligns with the conclusive analysis conducted by Plata *et al.* [39].

The dissolution results under identical conditions revealed the notable differences between the two rock samples. Commercial azomite rock exhibited superior solubility for the element K compared to basalt rock, mainly due to its significantly higher K content, three times that of basalt rock. Conversely, basalt rock showed higher dissolution results for the elements Ca and Al in the extraction solutions compared to commercial azomite rock. These findings align with the elemental composition analysis, confirming that basalt contains higher amounts of Ca and Al elements than commercial azomite rock (Figure 6). Consequently, the solution analysis results can be deemed reliable and consistent with the elemental composition of the two rock samples.

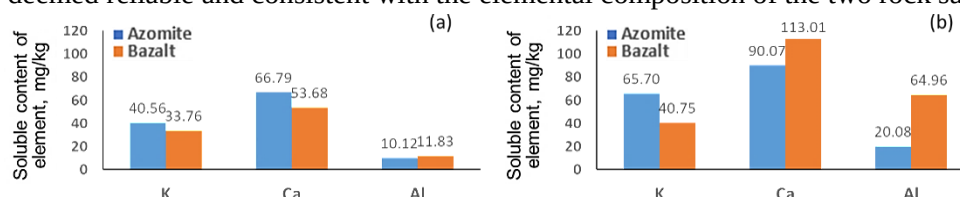


Figure 6. (A) Solubility of elements K, Ca, and Al in (A) distilled water and (B) acidic solution.

It is worth noting that K belongs to the primary macronutrients and has high solubility. Ca is classified as a secondary macronutrient, while Al is harmful to plants. When evaluating the ability of rock samples to provide nutrients, commercial azomite rock stands out for its higher concentration of K compared to basalt rock. Conversely, basalt rock provides substantial amounts of the secondary macronutrient Ca and the harmful element Al, surpassing commercial azomite rock in these elements. This characteristic of basalt rock can be viewed as both an advantage and a limitation when considering its use as a fertilizer.

4. CONCLUSIONS AND FUTURE WORKS

In conclusion, this article presents a comprehensive literature review and experimental investigation on volcanic rock powder as a sustainable alternative to conventional fertilizers for soil remineralization in agriculture. Several key findings and recommendations emerge, warranting further attention and research:

- Recognizing the role of primary and secondary macronutrients and micronutrients in crop nutrition is essential for selecting appropriate fertilizers to prevent soil depletion. Volcanic rock dust, with its rich nutrient composition, has proven effective in maintaining soil fertility and enhancing crop yields. Despite challenges in reducing chemical fertilizer usage, global interest in rock powder as an alternative is growing. Scientists are exploring its potential, aligning with sustainable agricultural practices and the demand for high-quality products. Using rock powder not only enhances food security but also reduces reliance on imported chemical fertilizers, thanks to advancements in technology that enable the production of functional fertilizers from this resource.

- Basalt rock has emerged as a popular subject for mineral fertilizer applications. Using high-energy ball mill equipment developed by Saigon Nanomaterials Co., Ltd., we processed porous basalt (from Nghe An province) into micro-nanometer particles, enhancing nutrient release efficiency. Compositional analysis reveals that basalt and commercial azomite rock contain minerals from the alkaline feldspar group, with key oxides such as SiO_2 , Al_2O_3 , K_2O , CaO , Fe_2O_3 , Na_2O , and MgO . While finely ground, both rocks have limited nutrient dissolution in distilled water. However, in an acidic solution (pH 2.2), the commercial azomite exhibits

higher dissolution of potassium (K), while the basalt sample shows higher dissolution of calcium (Ca) and aluminum (Al). Thus, basalt may have limitations in supplying macronutrients (K) but advantages in secondary macronutrients (Ca) compared to commercial azomite.

- Based on preliminary findings, additional research is warranted to assess the influence of finely ground particle size on the solubility of crucial secondary macronutrients and micronutrients like magnesium (Mg), iron (Fe), and copper (Cu). Further studies should examine plant growth response when fertilized with micronized basalt rock, scaling up experiments in laboratory and field settings. These investigations will provide insights into the effectiveness and potential advantages of using micronized basalt rock as an alternative to conventional fertilizers.

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REFERENCES

1. Tilman D., Cassman K., Matson P. - Agricultural sustainability and intensive production practices, *Nature* **418** (2002) 671-677. doi:[10.1038/nature01014](https://doi.org/10.1038/nature01014)
2. Bruulsema T. W., Fixen P. E., Sulewski G. D. - 4R plant nutrition manual: A manual for improving the management of plant nutrition, International Plant Nutrition Institute (IPNI), Norcross, GA, USA, 2012.
3. Uchida R. - Essential nutrients for plant growth: nutrient functions and deficiency symptoms. *Plant nutrient management in Hawaii's soils* **4** (2000) 31-55.
4. Provin, Tony L., and Mark L. McFarland - Essential nutrient for plants, Texas A&M Univ Syst US Dep Agric Cty Comm Court Texas Coop, 2013.
5. Almeida R. N., Navarro D. S., De Assis T. S., De Medeiros I. A., Thomas G. - Antidepressant effect of an ethanolic extract of the leaves of *Cissampelos sympodialis* in rats and mice, *J. Ethnopharmacol* **63** (3) (1998) 247-52. doi: [10.1016/S0378-8741\(98\)00086-5](https://doi.org/10.1016/S0378-8741(98)00086-5)
6. Sánchez P. A., Salinas J. G. - Low-input technology for managing Oxisols and Ultisols in tropical America, *Adv. Agron.* **34** (1981) 279-406. doi: [10.1016/S0065-2113\(08\)60889-5](https://doi.org/10.1016/S0065-2113(08)60889-5)
7. Leonardos O. H., Fyfe W. S., Kronberg B. I. - The use of ground rocks in laterite systems: an improvement to the use of conventional soluble fertilizers?. *Chem. Geol.* **60** (1-4) (1987) 361-70. doi:[10.1016/0009-2541\(87\)90143-4](https://doi.org/10.1016/0009-2541(87)90143-4)
8. Leonardos O. H., Theodoro S. H., Assad M. L. - Remineralization for sustainable agriculture: A tropical perspective from a Brazilian viewpoint, *Nutr. Cycl. Agroecosystem* **56** (1) (2000) 3-9. doi:[10.1023/A:1009855409700](https://doi.org/10.1023/A:1009855409700)
9. Hensel J.- Bread from stones: a new and rational system of land fertilization and physical regeneration, *AJ. Tafel* (1894).
10. Pinheiro S., Barreto S. B. - Agricultura sustentável, trofobiose e biofertilizantes, Porto Alegre: Junqueira Candiru, 1996. (in Portuguese).

11. Theodoro SH, de Paula Medeiros F, Ianniruberto M, Jacobson TK. Soil remineralization and recovery of degraded areas: An experience in the tropical region, *J. S. Am. Earth Sci.* **107** (1) (2021) 103014. doi: [10.1016/j.jsames.2020.103014](https://doi.org/10.1016/j.jsames.2020.103014)
12. Gillman G. P. - The effect of crushed basalt scoria on the cation exchange properties of a highly weathered soil, *Soil Sci. Soc. Am. J.* **44** (3) (1980) 465-8. doi:[10.2136/sssaj1980.03615995004400030005x](https://doi.org/10.2136/sssaj1980.03615995004400030005x)
13. Van Straaten P. - Farming with rocks and minerals: challenges and opportunities, *An. Acad. Bras. Cienc* **78** (2006) 731-47. doi: [10.1590/S0001-37652006000400009](https://doi.org/10.1590/S0001-37652006000400009)
14. Martin H. W., Sparks D. L. - Kinetics of nonexchangeable potassium release from two coastal plain soils, *Soil Sci. Soc. Am. J.* **47** (5) (1983) 883-887. doi:[10.2136/sssaj1983.03615995004700050008x](https://doi.org/10.2136/sssaj1983.03615995004700050008x)
15. Ramos C. G., Querol X., Oliveira M. L., Pires K., Kautzmann R. M., Oliveira L. F. - A preliminary evaluation of volcanic rock powder for application in agriculture as soil a remineralizer, *Sci. Total Environ* **15** (512) (2015) 371-80. doi:[10.1016/j.scitotenv.2014.12.070](https://doi.org/10.1016/j.scitotenv.2014.12.070)
16. Melamed R., Gaspar J. C., Miekeley N. - Pó-de-rocha como fertilizante alternativo para sistemas de produção sustentáveis em solos tropicais, *Fertilizantes: agroindústria e sustentabilidade*, Rio de Janeiro, CETEM/MCT, 2009, pp. 385-95 (in Portuguese).
17. Gillman G. P., Burkett D. C., Coventry R. J. - A laboratory study of application of basalt dust to highly weathered soils: effect on soil cation chemistry, *Soil Res.* **39** (4) (2001) 799-811. doi: [10.1071/SR00073](https://doi.org/10.1071/SR00073)
18. Escosteguy PA, Klamt E. Ground basalt as nutrient source, *Rev. Bras. Cienc. Solo*, 22:11-20 (1998) doi:[10.1590/S0100-06831998000100002](https://doi.org/10.1590/S0100-06831998000100002)
19. Blum W. E., Herbinger B., Mentler A., Ottner F., Pollak M., Unger E., Wenzel W. W. - Zur Verwendung von Gesteinsmehlen in der Landwirtschaft. I. Chemisch-mineralogische Zusammensetzung und Eignung von Gesteinsmehlen als Düngemittel, *Zeitschrift für Pflanzenernährung und Bodenkunde* **152** (5) 421-5 (1989). doi:[10.1002/jpln.19891520504](https://doi.org/10.1002/jpln.19891520504)
20. Bolland M. D., Baker M. J. - Powdered granite is not an effective fertilizer for clover and wheat in sandy soils from Western Australia, *Nutr. Cycl. Agroecosystems* **56** (1) (2000) 59-68. doi: [10.1023/A:1009757525421](https://doi.org/10.1023/A:1009757525421)
21. Manning D. A. - How will minerals feed the world in 2050?. *Proceedings of the Geologists' Association* **126** (1) (2015) 14-7. doi: [10.1016/j.pgeola.2014.12.005](https://doi.org/10.1016/j.pgeola.2014.12.005)
22. Bailey E. B. - James Hutton, founder of modern geology (1726–1797), *Proceedings of the Royal Society of Edinburgh, Section B: Biological Sciences* **63** (4) (1949) 357-68. doi: [10.1017/S0080455X00000229](https://doi.org/10.1017/S0080455X00000229)
23. Lacroix A. - *Minéralogie de Madagascar: Géologie, minéralogie descriptive*, A. Challamel, 1922 (in French).
24. Graham E. R. - Colloidal organic acids as factors in the weathering of anorthite, *Soil Sci.* **52** (4) (1941) 291-6.
25. Keller W. D. - *The Principles Of Chemical Weathering*, LWW, 1955, Aug. 1. DOI:[10.1097/00010694-195508000-00017](https://doi.org/10.1097/00010694-195508000-00017)
26. D'hotman de Vulliers O. - Sur des resultants d'études relatives a la rejuvenation de nos sols épuisés dès region humides par incorporation de poussière basaltique, *Rev. agric. suc. Ile Maurice* **26** (1947) (in French).

27. Il'chenko V. B. - O processo de decomposição das rochas alcalinas do Planalto de Poços de Caldas: estado de Minas Gerais. Escola de Engenharia, Universidade de Minas Gerais, Instituto de Pesquisas Radioativas, 1954 (in Portuguese).
28. Fraya R. - Rochas potássicas—possibilidades de aproveitamento para a indústria de adubos, Min. Metal, Rio de Janeiro (1952) (in Portuguese).
29. Kavalerdze W. C. - Nossos solos: formação: vida dinâmica: tratamento: conservação, Voz do Parana, 1978 (in Portuguese).
30. Motta A. C., Feiden A. - Avaliação do P em LE submetido a diferentes doses de basalto. Agrárias, **12** (47) (1992) 54 (in Portuguese).
31. Kiehl E. J. - Manual de compostagem: maturação e qualidade do composto, 1998 (in Portuguese).
32. Vanacore T. - A Rock Dust Primer (2015), https://rockdustlocal.com/uploads/3/4/3/4/34349856/a_rock_dust_primer.pdf (accessed 30 October 2023).
33. Campe J., Kittredge D., Klinger L. - The potential of remineralization with rock mineral fines to transform agriculture, forests, sustainable biofuels production, sequester carbon, and stabilize the climate., <http://remineralize.org/wp-content/uploads/2015/10/ODB1.pdf> (accessed 30 June 2023)
34. Swoboda P, Döring TF, Hamer M. Remineralizing soils? The agricultural usage of silicate rock powders: A review, Sci. Total Environ., Feb 10;807:150976 (2022) doi: [10.1016/j.scitotenv.2021.150976](https://doi.org/10.1016/j.scitotenv.2021.150976)
35. Azomite Mineral Products, Inc <https://azomite.com/> (accessed 30 June 2023).
36. Pavlis R. - Garden Myths: Book 1, CreateSpace Independent Publishing Platform (2017).
37. Huynh N. N. T., Van Anh T. H., Phuoc N. V., Son N. K. - A Comparative Study on the Use of Fine and Ultra-Fine-Crushed Lime Foliar Fertilizer for Rice Growth, In: Mohd Salleh, M.A.A., Che Halin, D.S., Abdul Razak, K., Ramli, M.I.I. (Eds.) Proceedings of the Green Materials and Electronic Packaging Interconnect Technology Symposium, EPITS 2022, Springer Proceedings in Physics, **vol 289**. Springer, Singapore. doi:[10.1007/978-981-19-9267-4_52](https://doi.org/10.1007/978-981-19-9267-4_52)
38. Azomite Mineral Products, Certificate of Typical Analysis <https://azomiteinternational.com/resources/coa.pdf> (accessed 11 October 2023).
39. Plata L. G., Ramos C. G., Oliveira M. L., Oliveira L. F. - Release kinetics of multi-nutrients from volcanic rock mining by-products: Evidences for their use as a soil remineralizer, J. Clean. Prod. **10** (279) (2021) 123668. doi: [10.1016/j.jclepro.2020.123668](https://doi.org/10.1016/j.jclepro.2020.123668)